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PLATE TECTONICS AND THE DISCRIMINATION OF UNDERGROUND EXPLOSIONS FROM EARTHQUAKES

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focal mechanism	volcanic structures	
surface waves	rupture zones	
Tibetan Plateau	size and duration of source	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

During the term of this contract, research was carried out in the following areas of interest to the contract:

1) A study of the velocity structure under the Tibetan Plateau using at least ten Tibetan earthquakes recorded by nearby WWSSN stations; — OVER

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2) A study of causes of variations in Ms/m_b relation for a central Asian earthquake sequence. The purpose of the study is to determine what factors other than source depth and focal mechanism control the surface wave magnitude for small events.

3) A study of the distribution of great shallow earthquakes.

4) A study to determine how well data from two or three of the High-Gain, Long-Period (HGLP) Seismograph Stations can prescribe an earthquake.

5) This study involves application of several numerical techniques for calculating theoretical seismograms.

6) Several studies have been conducted which involve the determination of stress orientation in island arcs from volcanic structures, the role of volcanic eruptions in the time history of major seismic gaps, or the mapping of fine structure within slabs of underthrusting lithosphere.

Line - Item 001a

1. Causes of M_s/m_b Variations within a Central-Asian Earthquake Sequence

A foreshock-mainshock-aftershock sequence in the Kirgiz-Sinkiang border region is studied to determine what factors other than source depth and focal mechanism control the surface-wave magnitude of small events. Using a comparative event technique, the mechanism and depth of the events are deduced from azimuthal radiation patterns of Love and Rayleigh waves. All the events appear to be 5-10 km deep, with predominantly thrust motion on a fault plane dipping about 30° from horizontal. Differences in mechanism and depth do not adequately explain the dramatic variation in surface wave amplitude within the series of aftershocks (see Figure 1). For example, one aftershock with m_b 5.2 generated surface waves roughly 12 times larger than another aftershock with m_b 5.0.

The earthquakes can be divided into two categories: those which excite long-period signals efficiently, such as the mainshock and several aftershocks; and those which do not, such as the foreshock and the majority of the aftershocks. The primary difference between the two groups may be the finite size or duration of the source. When observed teleseismically, the second group typically generates a very simple, short-period P-wave concentrated within the first 1 to 2 s (upper trace, Figure 2), suggesting nearly a point source. However, earthquakes within the first group generate a much more complex short-period P-wave, with substantial energy spread out over the first 10 to 15 s, as shown in the lower trace of figure 2 (duration of time marks is 2 s). The maximum amplitude of the short-period signal is not a very complete description of its character. A better description would include both amplitude and duration, as when the area of the envelope of the short-period record is measured. A comparison of these two measures of earthquake size is given in Figures 3 and 4, which show log of maximum amplitude (i.e., m_b) and area of short-period envelope, respectively, when plotted versus M_s. Using the area of the envelope in place of m_b will remove much of the scatter in M_s/m_b relations, without greatly increasing the effort involved in making the measurements. These observations suggest that finiteness of the source can play an important role in controlling M_s/m_b, even for earthquakes with body wave magnitude 4.8 or smaller.

2. Distribution of Great Shallow Earthquakes

Based on a world-wide survey of great earthquakes, Kelleher and McCann (1976) found that the distribution of large shallow earthquakes along subduction boundaries does not agree with the distribution pattern that might be predicted from a simple model

of plate tectonics. That is, along extensive sections of some island arcs large shocks occurred infrequently or not at all during recorded history. Most of these zones of long-term quiescence are nearly coterminous with segments of the margin where zones of seamounts, aseismic ridges or other bathymetric highs of the underthrust slab appear to be interacting with the subduction process. This spatial correlation suggests that at least some of the long-term absences of great shocks may result from a tectonic origin and not from temporary intervals of strain accumulation. Thus, major departures from classic subduction activity may develop where significant bathymetric features interact with a convergent margin.

From a similar survey of the source regions of seismic sea waves, or tsunamis, Kelleher (1976) indicates that many have important features in common, and that at the present time, there exists a number of sites which appear to fit these occurrence patterns of past tsunamis. Probably a majority of great tsunamis were generated along subducting margins by low-angle, thrust-type earthquakes which had rupture zones extending as much as several hundred kilometers along strike. For these great earthquakes, therefore, large vertical deformations of the sea floor occurred because of the large seismic moments (proportional to fault area x displacement), and despite the typically low angles of faulting (10° to 30°). Crude estimates of the size and location of some future shocks of this important class of earthquakes are possible by the technique of seismic gaps (segments of major plate boundaries that have not ruptured for many years). Thus, significant seismic gaps along subduction boundaries deserve attention as potential locations for future tsunamis.

A major new emphasis in research concerns the development of the inner wall of the trench and its relationship to the size and frequency of great earthquakes. The presence of numerous scarps and large deep-sea terraces within a well-developed pattern of imbricate thrust-faulting may be intimately related to and possibly an indicator of the episodic release of tectonic strain through great earthquakes.

3. Volcanic Structures as Indicators of Tectonic Stress

Orientation

A new method for obtaining tectonic stress orientation from volcanic structures, proposed by Nakamura (1969 and in press), was applied to the Aleutian and Alaskan volcanoes and volcanic fields. The method is essentially the recognition of the preferred orientation of radial and parallel dike swarm development by means of their probable surface manifestations, such as flank crater distribution. By the method one obtains for individual

volcanoes and volcanic fields primarily the trend of the maximum compression of the horizontal components of the tectonic stress. When the method is applied on a regional scale, one can further identify the trend, either as the maximum or as the intermediate axis of the tectonic stress.

The trends of the volcanic features which indicate the maximum compression of the horizontal components were obtained from fifteen volcanoes, including Buldir, the westernmost Aleutian volcano, and Iliamna volcano, near the eastern end of the Aleutian volcanic belt. Trends of the volcanic features generally coincide well with the azimuths of slip vectors for the relative motion between the Pacific and North American plates (Minster et al., 1974), thus providing evidence that the obtained horizontal directions at these volcanoes are for the maximum compressional axis of the tectonic stress.

General east-west trends were obtained from nine volcanoes and volcanic fields on islands and at the mainland coast of the Alaska-Bering Sea shelf. These volcanoes and volcanic fields are mostly of alkali-basalt (Smith et al., 1973) and are generally associated with normal faults of similar trends. Therefore, the obtained directions are most probably those of the intermediate axis, with the maximum compression axis in the vertical direction.

These results give strong support to the idea that the flank eruption on polygenetic volcanoes can be regarded as large-scale natural experiments for magmatic hydrofracturing. Moreover, they have important implications for the tectonics of island arcs and back-arc regions (such as the Kuril-Kamchatka arc and the Sea of Okhotsk in the U.S.S.R.): (1) Volcanic belts of some island arcs, at least the Aleutian arc, are under compressional stress. For such arcs, it is improbable to separate the various parts of the arc and form a marginal basin; (2) The compressional stress at the arc, probably generated by the underthrusting, appears to be transmitted across the entire arc structure, but is apparently replaced within several hundred kilometers by a different, tensional stress system in the back-arc region; (3) Both stress systems, the compressional and the tensional ones, are associated with volcanoes and volcanic fields, which, however, differ in the chemistry of their magma. This difference supports the idea that the back-arc stress system has its own source at considerable depth beneath the crust.

4. Volcanic Eruptions and Their Role in Seismic Gap Theory

Volcanic eruptions, now perhaps predictable events, may be used in long-term earthquake prediction. Kimura and McCann (in preparation) examine the possible relationship between major

volcanic eruptions and the occurrence of shallow thrust earthquakes along the Pacific margin. Although this study is still in its preliminary stages, some noteworthy results can now be reported.

Volcanic activity along the Kamchatka-central Kuril subduction zone was relatively active during the period 1923 - 1940. During the period 1940 - 1952 only five volcanoes were active, three in north Kamchatka and two in the Kuriles. In 1952 the great Kamchatka earthquake (M_s 8.25) occurred, rupturing $\sim$ 500 km along southern Kamchatka and the northern Kuriles. After this event volcanic activity increased north and south of the rupture area but remained at a low level in the region near the rupture zone. Similar relationships between volcanic eruptions and the large thrust earthquakes can be found (e.g., 1952 Aleutians, 1960 Chile, 1968 Hokkaido).

One possible model to explain the observed relationship is one which considers the elastic nature of the plate boundary in response to stresses applied to it. Prior to a large thrust event stresses would increase on a plate boundary. This stress would be regional in extent and involve a region several times the area of any future shock. This increased stress would induce volcanic eruptions through compression of magma source regions. If the future event is regional in extent (e.g., rupture zones several 100's of km large) then the decade of decreasing activity before the events could be due to dilatancy phenomena reducing the pore pressure in the magma source region and therefore the need for a volcanic eruption. After the earthquake stress in adjoining regions (gaps) would markedly increase especially in those regions that had been free of large thrust events in the several previous decades. This increase in tectonic stress would be reflected in an increase in volcanic activity.

Line - Item 001b

1. A Low Velocity Layer over the Tibetan Plateau

Surface wave data from more than ten Tibetan earthquakes have been digitized and moving window analyzed. The period range is 5 - 100 seconds with the corresponding group velocity window of 2.3 - 4.1 km/sec. The observed dispersion curves have been made and compared with their respective theoretical curves.

We have constructed for the Tibetan Plateau, a number of crustal and upper mantle models which we consider represent excellent average structures along the travel paths. One of them, TP-3 model, is shown in the following table:

RAYLEIGH WAVE

MODEL TP-3

Layer No.	Thickness	Dep.	P Velocities	S Velocities	Density
1	3.5000	3.5000	4.5000	2.6000	2.4000
2	34.5000	38.0000	5.9800	3.4500	2.8000
3	30.0000	68.0000	6.3000	3.6400	2.9000
4	INF	INF	8.0000	4.6000	3.4000

The main findings contained in our preliminary report still hold true except that there now appears to be some doubts regarding the existence of a relatively undeformed layer of low velocity sediments. Since the existence (or non-existence) of the undeformed layer of low velocity sediments proposed by Chen and Molnar (1975) has important tectonic implications, we have made some preliminary investigation into it. We think that the surface wave dispersion across the Ganges (to reach NDI and LAH stations) and the complexities in the Himalayas have such significant effect (especially in the short period range) that care has to be fully exercised when analyzing the high frequency surface waves.

Line - Item 001c

1. A Study of the Detection Capabilities of Several of HGLP Seismograph Stations

For the first study a swarm of earthquakes that occurred on the mid-Atlantic ridge in May of 1974 near 27.4°N and 44.4°W is being used as a test group to determine how accurately a few HGLP stations can locate an earthquake and determine its focal mechanism. This swarm was selected because it is within 50° of three HGLP stations: Ogdensburg, N.J., Kongsberg, Norway, and Toledo, Spain. The location (the distance and azimuth) of each earthquake in the swarm will be recomputed using the three HGLP stations and compared to the PDE locations as the standard. In addition to locating the events, magnitudes and focal mechanisms will be derived using data from only the three HGLP stations. These will be compared with those obtained by normal multi-station methods. Several digital filtering techniques have been employed to improve the detection capabilities of the HGLP stations. Band-pass and master event are among the techniques being used.

2. Possible Fine Structure in Underthrusting Lithosphere

Many studies have been reported concerning the development of trench-arc-backarc systems. Some of them, however, are quite ignorant of recent geophysical observations in these very complex regions. Dr. Yoshii has compiled some geophysical observations in the northeastern Japan, one of the most typical trench-arc-backarc systems. From the abundant observation data, maps and cross sections for bathymetry, crustal structure, gravity anomaly, heat flow and earthquakes were constructed.

The extensive analyses of earthquakes, gravity and heat flow have been made so far. Reconstruction of the earthquake hypocentral cross section by using pP-depths reported by the International Seismological Centre implies surprising concentration of the earthquakes on a plane of only 15 km thick extending from the trench axis down to the depth of about 300 km. Moreover, the second plane can be clearly seen about 40 km below this main plane. Focal mechanism solutions of several events on this highly detailed earthquake distribution help our understanding of complex motions acting on the trench-arc-backarc system, such as bending and unbending of the oceanic plate and thrustal motion between the continental and oceanic plates.

Line - Item 001f

1. Numerical Techniques for Computing Seismograms of Several Body Phases

A study is in progress of a technique that calculates seismograms for body waves which undergo turning point interactions. The method involves numerical (but cheap) computations in the complex ray parameter plane, of a type which has important differences from Cagniard's method. We use a complex velocity profile to account for attenuation, and the uniformly asymptotic method of Langer to account for frequency-dependence of reflection-transmission coefficients. The ray systematics for studying a high velocity region over a low velocity (e.g., the core-mantle boundary), with associated tunnelling effects, have been known for several years. However, the (geophysically) more common case, of low velocity region over high, leads to ray systematics which have only recently been understood. The work of Nussenzveig which correctly evaluates all the waves in the high velocity medium which are repeatedly refracted back up to, and reflected from, the low velocity medium. The Debye ray expansion is not made, in the region where it is poorly convergent.

Initial indications, from seismograms observed and calculated near the point D of PKP waves (which is the critical distance for

K waves incident from fluid core upon solid inner core), are that impedance jumps are greater than had been supposed, and that the amplitude maximum associated with the critical distance is displaced to shorter distances at lower frequencies. We have also found that computed seismograms for SmKS (m = 1, 2, ...) exhibit many non-ray effects in the distance range 100° - 125°. Such waves are an excellent example of the way in which successively higher-order reflections (SKKS, SKKKS, etc.) have arrivals within the waveform of previous reflections. The total seismogram for all the multiples is exceedingly sensitive to velocity gradient in the outer fluid core, and initial indications are that the Jeffreys-Bullen gradient is correct.

We are currently testing our method, for S waves interacting with upper-mantle discontinuities.

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Action required by the Government:

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Chun, K.Y., and T. Yoshii, Crustal structure of the Tibetan Plateau: A surface wave study by a moving window analysis, Bull. Seism. Soc. Am., in press, June, 1976.

Gregersen, S., and L. E. Alsop, Mode conversion of Love waves at a continental margin, Bull. Seism. Soc. Am., 66, 1855-1872, 1976.*

Tatham, R.H., D. W. Forsyth, and L. R. Sykes, The occurrence of anomalous seismic events in eastern Tibet, Geophys. J. R. astr. Soc., 45, 451-481, 1976.*

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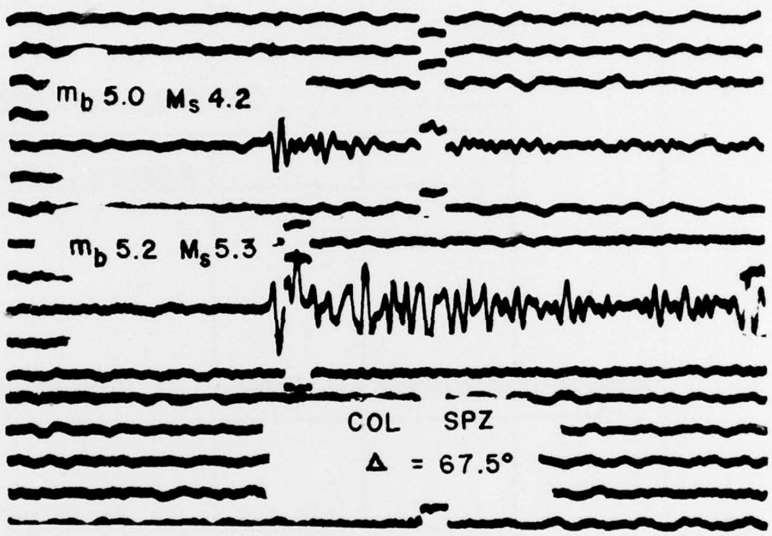

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m_b 5.2 M_s 5.3
COL SPZ
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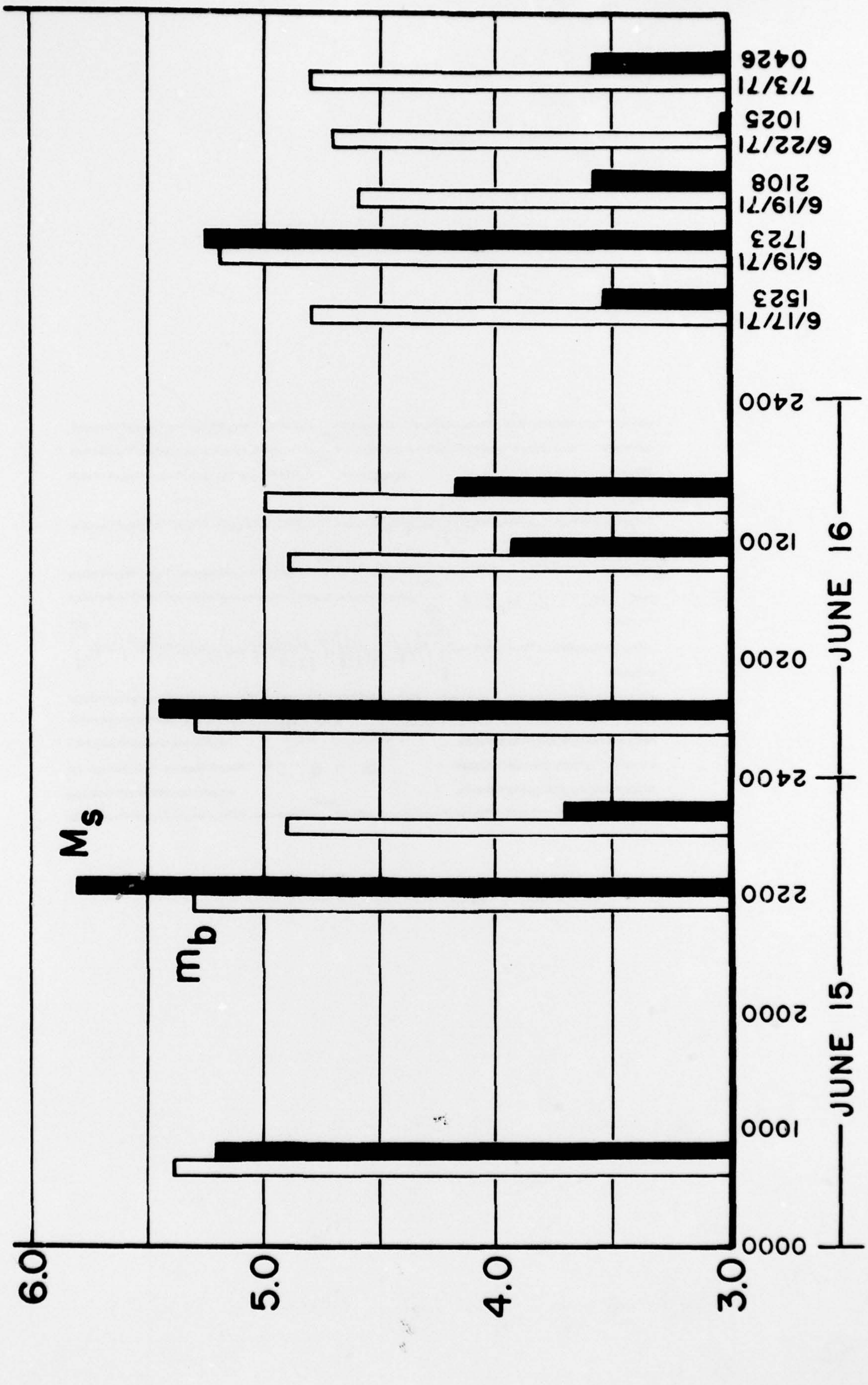
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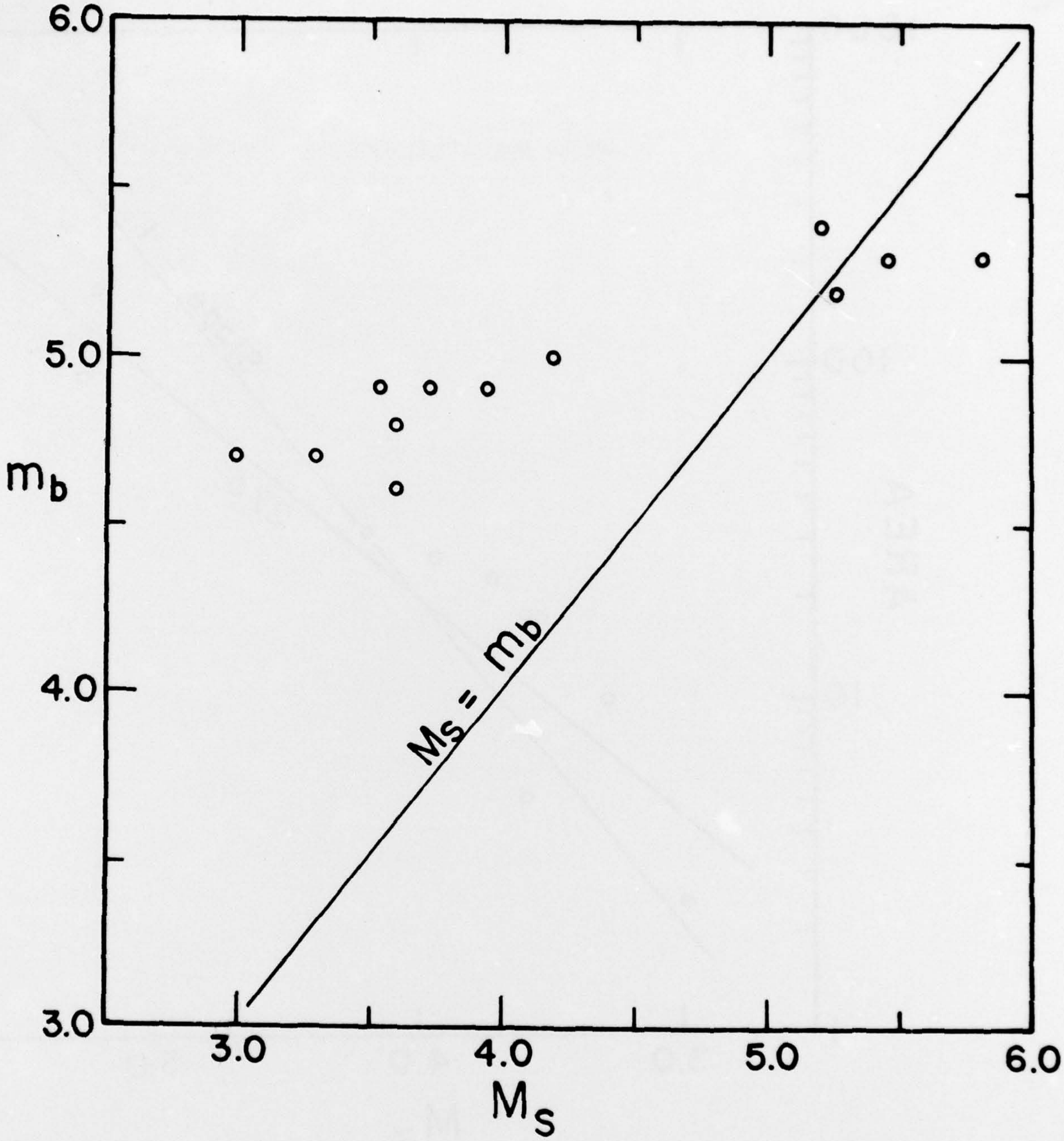
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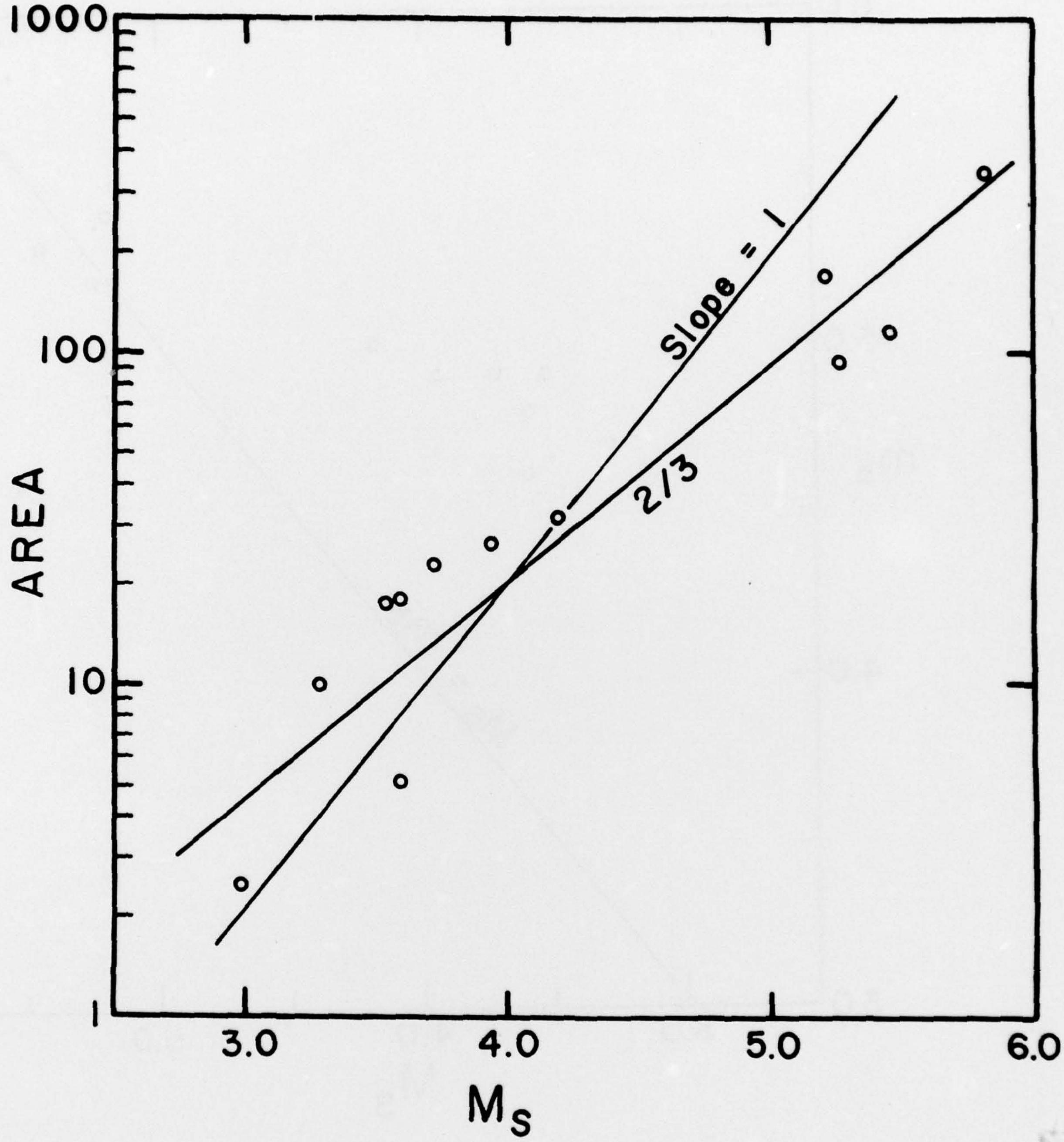
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